Continuous variable qubit state engineering

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Continuous variable qubit state engineering

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Abstract. We present an experiment where a range of highly non-classical optical states were generated and fully characterized. As a class they can be considered as realizations of a qubit state in a squeezed vacuum/squeezed photon basis. The central technique of displaced photon subtraction will have applications to quantum computing with coherent states.

Keywords: Quantum optics, quantum information, continuous variables, photon subtraction
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Inspired by a number of proposals for coherent state-based quantum computing (CSQC) [1, 2, 3], we suggested a method for preparation of arbitrary superpositions of two opposite-phase coherent states based on photon-subtraction from squeezed vacuum [4]. The idea of CSQC is to encode logical qubits into the physically higher-dimensional coherent states $|\alpha\rangle$ and $|-\alpha\rangle$. For large amplitudes the two states are basically orthogonal, while for small α they have a finite overlap – nonetheless, this scheme is capable of fault-tolerant quantum computing with certain advantages (as well as disadvantages) over traditional single photon-encoded schemes [5]. One drawback is the difficulty of producing superpositions of coherent states, something that requires non-Gaussian operations. Recently, though, the idea has gained considerable traction after a scheme [6] for how to relatively simply generate the diagonal states $|\psi_\pm\rangle \propto |\alpha\rangle \pm |-\alpha\rangle$ has been demonstrated in a number of labs around the world [7, 8, 9, 10, 11, 12, 13]. For small amplitudes $|\alpha| \lesssim 1.5$, the photon subtracted squeezed vacuum state $\hat{a}\hat{S}(r)|0\rangle$ resembles closely $|\psi_-\rangle$, while the two-photon subtracted squeezed vacuum $\hat{a}^2\hat{S}(r)|0\rangle$ is close to $|\psi_+\rangle$ for suitable values of the squeezing parameter r.

In experimental coherent state superposition generations, the squeezed vacuum resource is prepared by down-conversion in nonlinear crystals or waveguides, either in pulsed single-pass or with a cw pump and cavity enhancement. The photon subtraction is implemented by a weakly reflecting beam splitter with the reflected light directed towards one or two single photon counting modules or a photon-number resolving detector. A photon detection event there heralds the subtraction of one or more photons in the mode of the transmitted beam that is correlated to the photon(s) responsible for the detection event. For verification of the produced non-classical state, its Wigner function can be reconstructed from a homodyne tomographic measurement. Heavy spectral and/or spatial filtering is needed in the photon subtraction channel in order to eliminate detection of modes that are uncorrelated with the observed output mode. The states obtained in the different experimental studies are highly non-classical as indicated by

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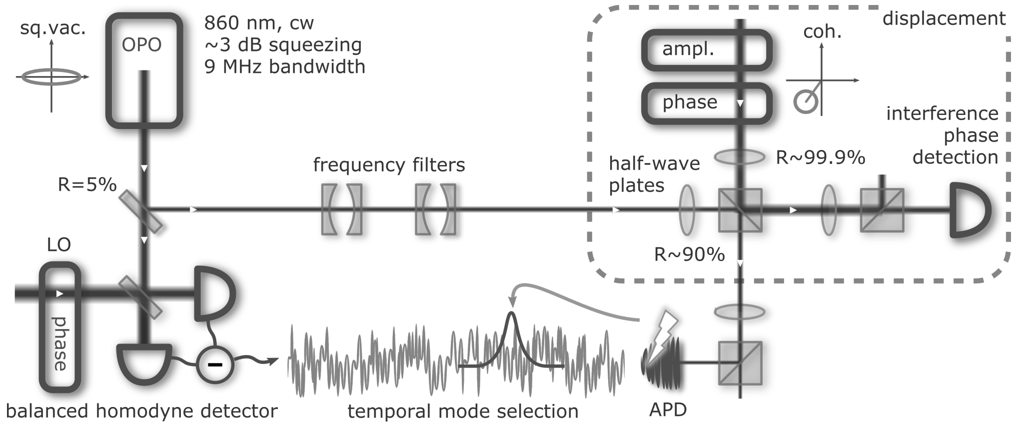

FIGURE 1. Experimental setup. An initial squeezed vacuum state from a continuously pumped optical parametric oscillator (OPO) is subjected to a 5% tapping with the remaining 95% proceeding towards a homodyne detector (HD) for output state characterization. The tapped beam is spectrally filtered by two Fabry-Perot resonators in order to eliminate the many non-degenerate longitudinal OPO cavity modes that are uncorrelated with the mode observed by the HD. After filtering, the beam is displaced by interfering it on an unbalanced polarizing beam splitter with a coherent beam with variable phase and amplitude. The resulting beam is observed by a single photon sensitive avalanche photo diode (APD). Conditioned on a detection event, we sample the homodyne current in an interval around the click time and subsequently temporally filter and integrate the current according to the correlation between the two beams. A full state tomography is carried out by repeating the measurement many times with different settings of the local oscillator (LO) phase. Refer to [14] for more details on the displacement operation, the phase locking mechanism, and the various filterings.

their negative Wigner functions. Unfortunately, because of the very fragile nature of the coherent state superpositions, various experimental imperfections and certain inherent limitations in the implementations, fidelities with the $|\psi_\pm\rangle$ states are so far limited to around 55-70%. For realization of CSQC schemes, one challenge is to improve on these fidelities. Another challenge for CSQC will be to get access to experimentally feasible state manipulation techniques in order e.g. to perform quantum gates. In particular, preparation of arbitrary qubit states in the $|\pm\alpha\rangle$ basis would be quite useful. Following the path of the experiments mentioned before, we proposed in [4] to perform an operation that is a superposition of $\hat{a}$ and $\hat{a}^2$ on an input squeezed vacuum. This would generate a superposition of approximations to the $|\psi_\pm\rangle$ states, equivalent to an arbitrary qubit $a|\alpha\rangle + b|-\alpha\rangle$. Such a superposition operation can be implemented by two photon detectors in the subtraction channel, but with a phase space displacement $\hat{D}(\beta)$ applied to the beam immediately before one of the detectors. This displacement, done by interfering the beam with a weak coherent state on a highly asymmetric beamsplitter, entails a projection onto $\beta|0\rangle + |1\rangle$ rather than $|1\rangle$ on the click of the following detector.

We have demonstrated experimentally this method of displaced photon subtraction [14], although we used only one photon detector. Our generated states are therefore superpositions of squeezed vacuum and single-photon subtracted squeezed vacuum (equivalent to a squeezed photon). These two states are orthogonal, so we can describe the targeted states as qubits in a squeezed state basis with the Bloch sphere representation $|\psi\rangle = \cos\frac{\theta}{2}\hat{S}(r)|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\hat{S}(r)|1\rangle$. The setup is illustrated and described in Figure 1.

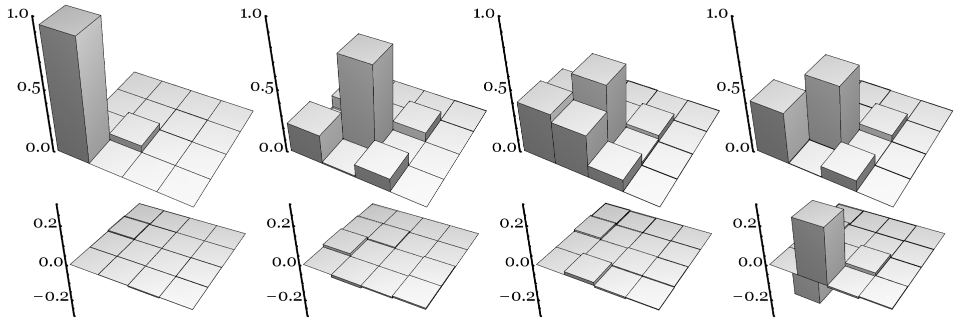

FIGURE 2. Squeezed number state basis density matrices of representative reconstructed output states. From left to right: Squeezed vacuum, squeezed photon, a state generated with a displacement beam of 1/3 the intensity (at the APD) of the squeezed trigger beam and with 180° relative phase, and finally a similar state but with 90° relative phase. The upper matrices are real parts, lower matrices are imaginary.

By tuning the phase and amplitude of the displacement beam we can prepare the output in any desired (although impure) qubit state. To show this, we carried out a large number of state preparations for different displacement parameters, each time characterizing the state by full homodyne tomography based on 360,000 samples distributed on 12 fixed, evenly distributed phases in the interval $[0;\pi[$. From the reconstructed density matrices we could calculate the Wigner functions, resulting in a whole zoo of different non-classical states with varying degrees of negativity and asymmetries in phase space.

For the general classification of the various states, we turn to the previously mentioned Bloch sphere representation. By transforming the density matrices from the normal number state basis to a squeezed number state basis, $\hat{S}(r)|n\rangle$, we find that all the states essentially are confined to the lowest 2-dimensional subspace as seen in the examples in Figure 2. This subspace corresponds to the squeezed state qubit, so by neglecting the higher order terms we can calculate the Bloch parameters θ, ϕ for each of the generated states. In Figure 3 we have plotted the Wigner functions of all the states and positioned them at their respective locations in the Bloch sphere. The experimentally obtained states are clearly not pure; in particular the squeezed vacuum and squeezed photon states are not perfectly orthogonal (their overlap is 0.26), so the states are not usable for quantum information purposes as such, but they still serve as a clear demonstration of the potential of the displaced photon subtraction method. In fact, this method is also applicable to genuine coherent state superpositions: $\hat{a}|\psi_{\pm}\rangle \propto |\psi_{\mp}\rangle$, so starting from one of the $|\psi_{\pm}\rangle$ states, any superposition of them can be obtained. Furthermore, the operation can be used in implementations of quantum gates with coherent states [15], and superpositions of 0-, 1-, and 2-photon number states were generated by a similar procedure [16]. We can conclude that the photon-subtraction operation combined with phase space displacements is a very convenient and useful tool for state preparation and manipulation.

As a final note, let us mention that we have developed a comprehensive and accurate multimode model for the experiment, taking all relevant parameters into account, and compared it with the observations [17]. Furthermore, an interactive Java applet showcasing the Wigner functions along with their detailed parameters is available from our website at `http://www2.nict.go.jp/w/w115/about/53kasai_eng.html`.

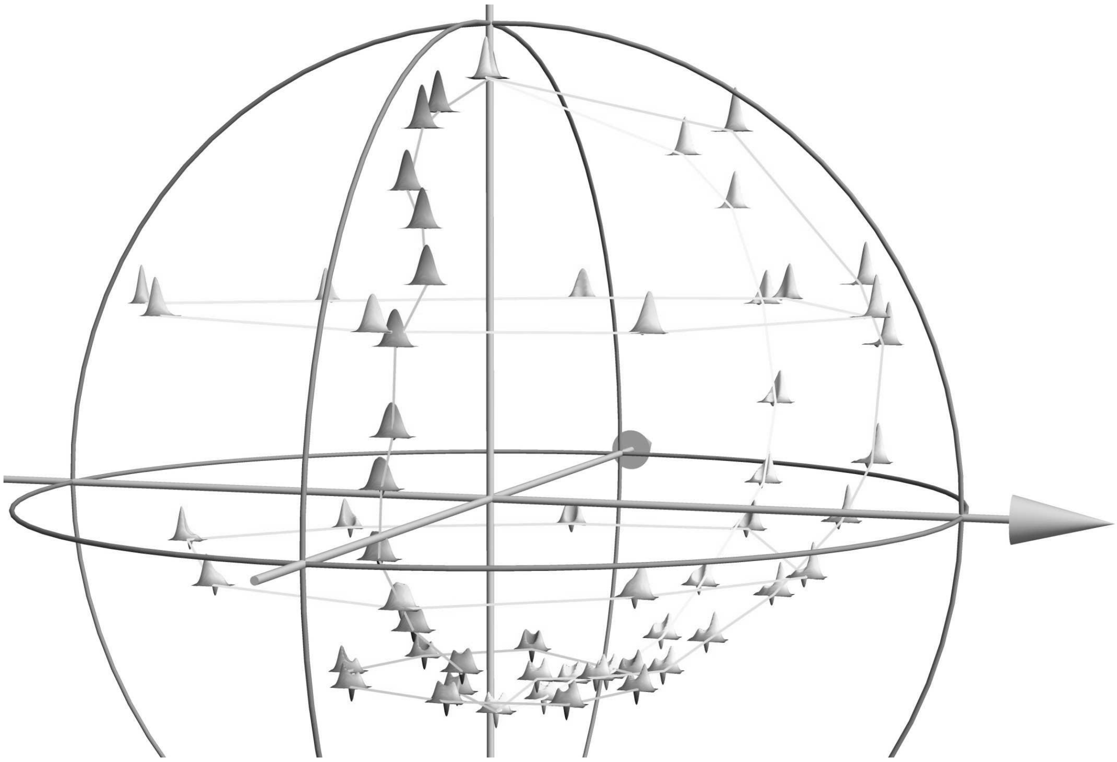

FIGURE 3. Bloch sphere with the experimentally generated and reconstructed qubit states plotted by their Wigner functions. The north pole basis state is $\hat{S}(r)|0\rangle$ and south is $\hat{S}(r)|1\rangle$, both with $r = 0.38$.

REFERENCES

1. P. T. Cochrane, G. J. Milburn, and W. J. Munro, *Phys. Rev. A* **59**, 2631–2634 (1999).
2. H. Jeong, and M. S. Kim, *Phys. Rev. A* **65**, 042305 (2002).
3. T. C. Ralph, A. Gilchrist, G. J. Milburn, W. J. Munro, and S. Glancy, *Phys. Rev. A* **68**, 042319 (2003).
4. M. Takeoka, and M. Sasaki, *Phys. Rev. A* **75**, 064302 (2007).
5. A. P. Lund, T. C. Ralph, and H. L. Haselgrove, *Phys. Rev. Lett.* **100**, 030503 (2008).
6. M. Dakna, T. Anhut, T. Opatrný, L. Knöll, and D.-G. Welsch, *Phys. Rev. A* **55**, 3184–3194 (1997).
7. A. Ourjoumtsev, R. Tualle-Brouri, J. Laurat, and P. Grangier, *Science* **312**, 83–86 (2006).
8. J. S. Neergaard-Nielsen, B. M. Nielsen, C. Hettich, K. Mølmer, and E. S. Polzik, *Phys. Rev. Lett.* **97**, 083604 (2006).
9. K. Wakui, H. Takahashi, A. Furusawa, and M. Sasaki, *Optics Express* **15**, 3568–3574 (2007).
10. A. Ourjoumtsev, H. Jeong, R. Tualle-Brouri, and P. Grangier, *Nature* **448**, 784–6 (2007).
11. H. Takahashi, K. Wakui, S. Suzuki, M. Takeoka, K. Hayasaka, A. Furusawa, and M. Sasaki, *Phys. Rev. Lett.* **101**, 233605 (2008).
12. N. Namekata, Y. Takahashi, G. Fujii, D. Fukuda, S. Kurimura, and S. Inoue, *Nature Photonics* **4**, 655–660 (2010).
13. T. Gerrits, S. Glancy, T. Clement, B. Calkins, A. Lita, A. Miller, A. Migdall, S. Nam, R. Mirin, and E. Knill, *Phys. Rev. A* **82**, 031802(R) (2010).
14. J. S. Neergaard-Nielsen, M. Takeuchi, K. Wakui, H. Takahashi, K. Hayasaka, M. Takeoka, and M. Sasaki, *Phys. Rev. Lett.* **105**, 053602 (2010).
15. P. Marek, and J. Fiurášek, *Phys. Rev. A* **82**, 014304 (2010).
16. E. Bimbard, N. Jain, A. MacRae, and A. I. Lvovsky, *Nature Photonics* **4**, 243–247 (2010).
17. M. Takeoka, J. S. Neergaard-Nielsen, M. Takeuchi, K. Wakui, H. Takahashi, K. Hayasaka, and M. Sasaki, *Journal of Modern Optics* (2010), DOI: 10.1080/09500340.2010.533205.